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FAA ACCEPTANCE TESTS ON THE NAVIGATION SYSTEM USING TIME AND RANGING GLOBAL POSITIONING SYSTEM Z-SET RECEIVER

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Final Report

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16. Abstract

This report describes Federal Aviation Administration (FAA) acceptance tests on the Navigation System Using Time and Ranging (NAVSTAR) Global Positioning System (GPS) Z-set receiver which were conducted in a United States Air Force (USAF) System Command C-141 aircraft over the instrumented range located at the Yuma Proving Ground. The Yuma laser tracking system computed a reference trajectory against which the GPS receiver solution was compared. Data from five flights, totaling over 6 hours, are presented with the objective of assessing Z-set capabilities to meet civil aviation requirements for nonprecision approaches.

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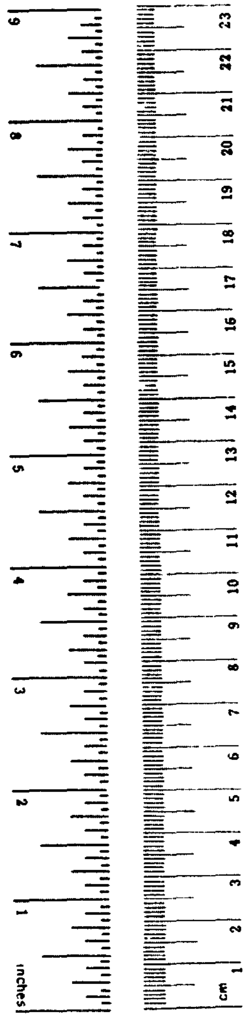
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

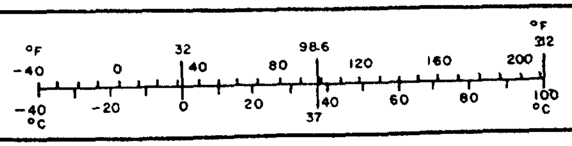
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

The NAVSTAR Global Positioning System (GPS) is a prototype Department of Defense (DOD) space-based radio navigation system which is managed by the Joint Program Office (JPO) in the Air Force System Command (AFSC) (reference 1). The fully deployed system is projected to permit military and selected civil users to determine their position to within 25 meters horizontal (2 distance root mean square (drms)) accuracy and within 30 meters vertical (2 sigma) accuracy. (The 2 drms value refers to the probability that a circle of given radius will contain at least 95 percent of the data points.) Although DOD is responsible for the development and deployment of GPS, the Federal Aviation Administration (FAA) has the responsibility to evaluate GPS as a potential navigation system for civil aviation (reference 2).

The FAA and AFSC agreed to perform acceptance tests on a DOD Z-set receiver before it was released to the FAA for independent test and evaluation. The purpose of the acceptance tests were: (1) to familiarize FAA engineers and pilots with GPS user equipment and the DOD test program, and (2) to investigate the general capabilities of the Z-set. The test flights were conducted by the DOD over the instrumented range of the Yuma Proving Ground in Arizona in an AFSC C-141 aircraft with FAA observers aboard. The aircraft position was determined by a laser tracker and compared to the GPS receiver derived position. The JPO previously reported Z-set accuracy to be within 50 meters (2 sigma) in three dimensions (reference 3).

In this report, over 6 hours of data from the Yuma tests are summarized. The analysis is directed towards determining whether the Z-set and GPS meet FAA requirements for nonprecision approaches: 100 meters, 2 drms accuracy in the horizontal plane. The findings (solely those of the FAA as per agreement) generally support previous results reported by JPO.

TEST CONFIGURATION

SATELLITES.

The GPS satellites broadcast position and time information on 1227.60 and 1575.42 megahertz (MHz). Spread spectrum modulation is employed to take advantage of its inherent capabilities for high resolution ranging, low density power spectrum, code division multiplexing, and high immunity to jamming. Each satellite is assigned two pseudonoise codes: P, which provides for precise measurement of time, and C/A (coarse acquisition and only on the higher frequency), which provides for easy lock-on and less precise measurement. The satellites carry atomic clocks (and backup crystal oscillators) to maintain frequency stability for accurate measurements. User position is determined by processing signals from four satellites and solving four equations with four unknowns (three time differences of arrival for range, and a time correction factor to synchronize the receiver clock).

At the time of the tests, NAVSTAR vehicles 1 through 4 were in orbit and operational. The four satellites were visible over Yuma for approximately 1.5 hours each day. The geometric dilution of precision (GDOP) value during most of the test period indicated a good satellite arrangement for accurate navigation. NAVSTAR 4 dropped from an elevation angle of 30° to 10° above the horizon in approximately

50 minutes, and it was the first satellite in the constellation to set. Since NAVSTAR 1 and 2 were operating on backup crystal controlled clocks, the space segment errors were generally larger than what would be expected for the fully deployed satellite system.

Z-SET RECEIVER.

The Z-set, built by Magnavox, is viewed as a fairly sophisticated first-generation navigator for transport-class aircraft. It was built with stringent design-to-cost goals (approximately $30,000 per item in production), resulting in some compromise in performance. The set processes C/A signals sequentially from the satellite constellation. The resident 8-state Kalman filter computes user position in earth-centered earth-fixed (ECEF) coordinates, velocity, time error, and frequency error usually every 1.2 seconds (the normal sequence time per satellite). The Z-set is programmed to drop a satellite once it falls to an angle between 10° and 15° above the horizon. The receiver used in the FAA tests (serial number 6, software version number 9) accepts encoded barometric altimeter data (increments of 100 feet) into the navigation solution when tracking less than four satellites.

In some test flights a more sophisticated X-set or Y-set was also aboard, and its performance was compared to the Z-set. These receivers are also built by Magnavox, have Hewlett-Packard 2100 series computers, process both satellite navigation frequencies and codes, and may be interfaced to an inertial measurement unit. The four-channel X-set tracks signals from four satellites simultaneously, whereas, the single-channel Y-set does so sequentially.

The GPS antennas were mounted on top of the C-141 fuselage (see figure 1) near the leading edge station for the wings. A conical spiral antenna with hard hat radome (Microwave Specialities Corporation model 1133) was utilized for the Z-set. It can be shown that the position determined by a GPS receiver is located at its antenna station.

AIRBORNE DATA COLLECTION SYSTEM.

The GPS data collection system is operated by the user equipment field test instrumentation (UFTIN) computer program. The system is capable of simultaneously recording and displaying parameters from two different GPS receivers. The instrumentation hardware consists of a Hewlett-Packard 2100 series data processor, a memory loader, an engineering control unit, two digital magnetic tape recorders, two engineering display units (EDU's), provisions for an atomic clock and/or inertial measurement unit (if required), and range interface. Receiver position, velocity, and time data are telemetered to the Yuma computer complex.

When the Z-set undergoes test, an interface data processor (IDP) (another 2100 series computer) is utilized primarily to format outputs to the data collection system. The IDP has direct memory access to the LSI-11 microcomputer in the Z-set through a special interface card and line driver. Data transfer between the Z-set and IDP is based on the occurrence of an event (a group of data blocks) in the set. Z-set data, such as selected satellite constellation, time, pseudorange measurement, 3-dimensional position in ECEF coordinates, various residual errors, fault indications, etc., are forwarded by the IDP to the data collection system in the same format as X- and Y-set parameters. Z-set update rates to the IDP are dependent upon higher priorities associated with the basic receiver/processor functions.

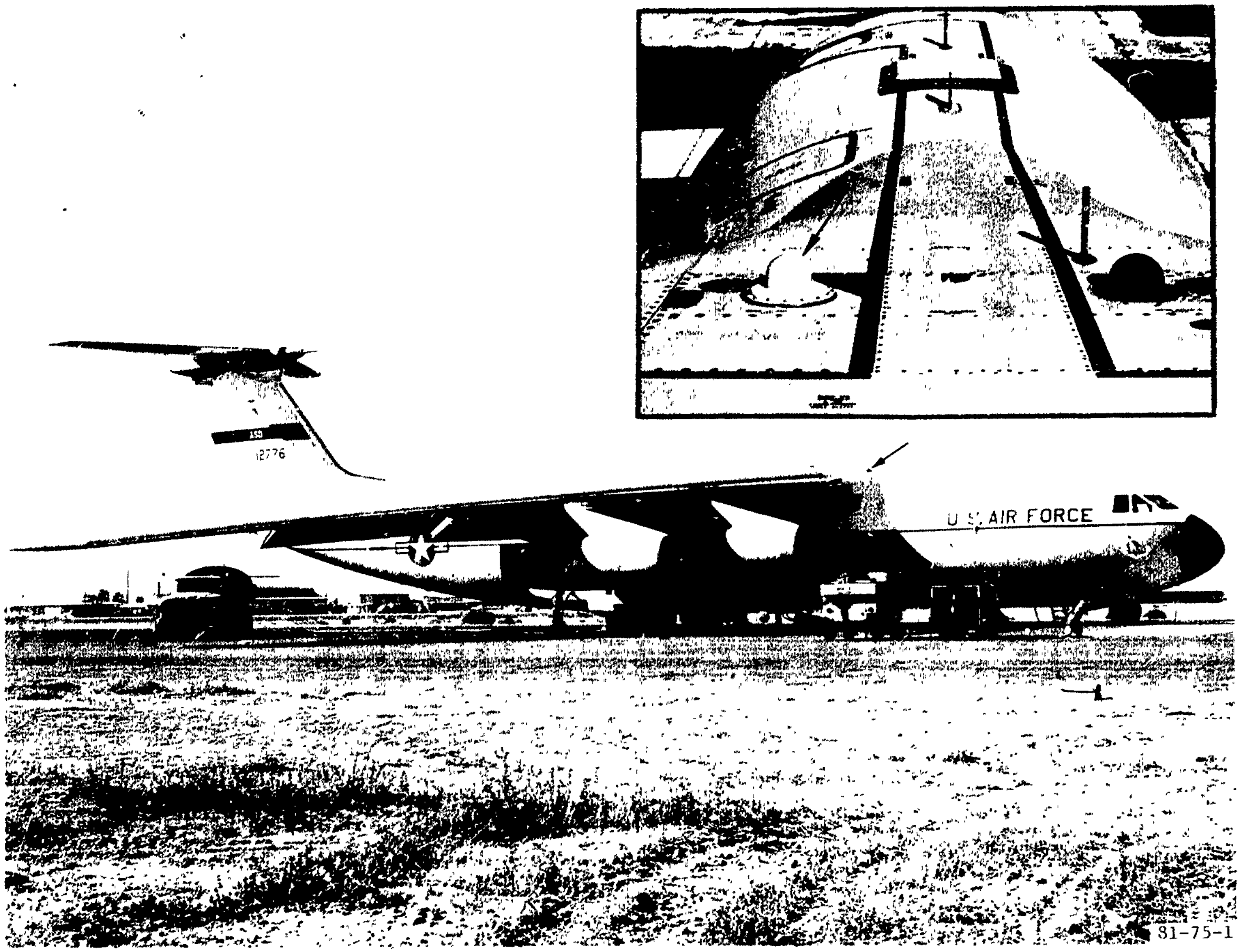

FIGURE 1. C-141 AIRCRAFT USED FOR FAA ACCEPTANCE TESTS — INSERT SHOWS Z-SET ANTENNA (WHITE RADOME - MICROWAVE SPECIALTIES CORPORATION, MODEL 1133)

In the normal navigation mode, the position is updated every 1.2 seconds (the sequence time per satellite).

YUMA TEST RANGE FACILITIES.

The computer/communications complex at the Yuma Proving Ground provides command and control functions during GPS tests. It encompasses the Yuma mission control, test range, tracking, telemetry (range time to the aircraft and GPS receiver data from the aircraft), communications data processing, meteorological, and the Inverted Range Control Center (IRCC) facilities.

The IRCC consists of ground transmitters to simulate satellite signals (not utilized in Z-set tests) and a ground truth monitoring system. An X-set driven by an atomic clock serves as the fiducial receiver. This unit is situated in an environmentally protected shelter on the Yuma test range, and its output is forwarded to the computer complex. The difference between the ground truth receiver determined position and its surveyed location gave the local position errors resulting from the space segment errors.

The Yuma range utilizes the Precision Automated Tracking System (PATS), built by General Telephone and Electronics (GTE)-Sylvania, and near real-time filtering procedures to provide a reference trajectory against which the GPS receiver solution is compared. PATS consists of three identical lasers (located at strategic surveyed points) which track optical retroreflectors mounted on the top and bottom of the C-141 fuselage. The Yuma central computer complex filters and smoothes the position data which are determined at the antenna station(s) for the airborne GPS receiver(s) in ECEF coordinates. Aircraft velocity and acceleration are calculated from the smoothed trajectory data, and trajectory points from each laser are compared every 200 milliseconds. Data from the laser closest to the aircraft are recorded onto digital magnetic tape at five samples per second. The laser-determined solution is then interpolated at the update time of the telemetered GPS results (arbitrary update intervals). Differences between the GPS and laser tracker solutions are displayed at the Yuma mission control center to provide a "quick look" assessment in near real-time of user equipment performance. Yuma reports that the trajectory solution is accurate to within 1 meter (under normal tracking conditions). Overall space segment status is given by the ground truth monitor.

FLIGHT TEST CONDITIONS.

The FAA and JPO detachment at Yuma agreed upon a series of normal and expedited flight maneuvers for the acceptance tests. The flight patterns were constrained by the test range airspace and terrain surrounding the Laguna Army Airfield. For example, the laser tracking system could not follow the testbed aircraft throughout a normal approach to the airfield. The principal flight pattern involved racetrack orbits which allowed 180° turns with varied bank angles and roll rates, different climb/descent rates, and different aircraft attitudes. The racetrack measured typically 5,000 by 20,000 meters, with the straight leg portions in the north-south direction. The overriding factors governing the missions were aircraft availability, satellite window period, space segment errors, and JPO priorities.

All flights were performed in an AFSC C-141 aircraft which is a heavy, subsonic, four-engine jet transport with conventional body, high wing, and T-tail. The aircraft was crewed by the 4950th Test Wing. JPO engineers operated the GPS

instrumentation; FAA personnel served as observers and/or alternate project engineers aboard the aircraft. The satellites were uploaded with fresh ephemeris data, and the GPS receiver made airborne acquisitions immediately before the tests began to minimize space segment errors.

The initial goals were either essentially met or exceeded in the tests: speed from approach to cruise, acceleration ±3 knots per second, 180° turns with bank angle to 45°, turn rate to 6° per second, roll rate to 8° per second, climb/descent +2000 to -6000 feet per minute, pitch ±15° for short durations, pitch rate to 3° per second, altitude from approach to high cruise (restricted by range to approximately 20,000 feet), and combinations of the above utilized in normal civil operations.

RESULTS

TEST DATA.

The FAA received post-flight data packages consisting of mission logs and computer generated plots prepared by the Yuma processing center. The mission logs gave information on range system status, project equipment status, a verbal commentary on aircraft dynamics, satellite upload times, and other relevant points. The aircraft trajectory and difference values were displayed on a series of data plots for nominally 1,400-second intervals (approximately three racetrack orbits). The aircraft trajectory contained the reference position and velocity curves computed in near real-time. The difference or delta plots refer to the differences between the smoothed trajectory values and the telemetered (airborne) receiver determinations, where the former are interpolated to the time of the receiver update. The delta plots are viewed as GPS receiver errors which include space segment errors.

Yuma provided computer plots of the position differences in x (true east error), y (true north error), z (positive vertical error), ρ (x-y horizontal plane error), and r (three-dimensional error) versus time. The mean and root mean square (rms) values for the differences plots were computed over the nominal 1,400-second flight segment and printed on the data plots. However, the calculations for the expectation values did not include those time intervals where there was an obvious range or aircraft instrumentation problem (for example, loss of laser lock or telemetry). In addition, ground truth receiver errors (differences between its computed and surveyed positions) were given.

Figure 2 illustrates a typical ρ versus time plot (taken from the September 19, 1979 mission). Intervals 1 and 2 show Z-set behavior for 180° turns with 30° bank angles at the ends of a constant altitude (19,700 feet) racetrack pattern. Note that the receiver position error increases in the turns. During interval 3, the C-141 entered into an emergency spiral descent making a 2-gravity (g) turn at a 60° bank angle (the pilot banked the aircraft shortly before beginning the descent). The Z-set lost a satellite during the descent and reacquired it and overall position accuracy before maneuver completion. The instantaneous value of ρ exceeded 400 meters for approximately 9 seconds, 200 meters for 55 seconds, and 100 meters for 80 seconds over a 138-second period during this maneuver.

Interval 4 illustrates the turns to the base leg and final leg during a missed approach to the Laguna Army Airfield on the Yuma range. The loss in laser track

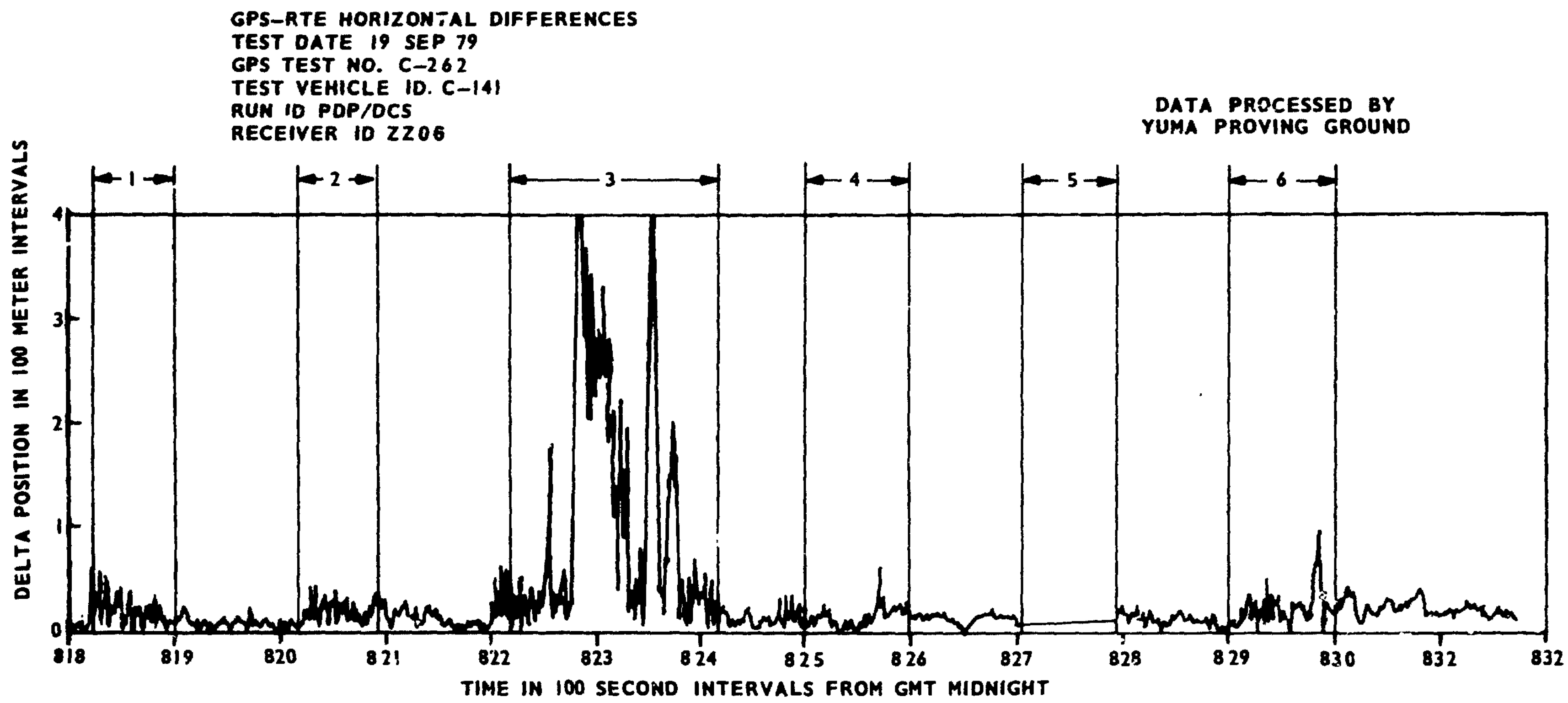

FIGURE 2. Z-SET POSITION ERROR IN THE HORIZONTAL PLANE VERSUS TIME

(interval 5) occurred when the aircraft turned into the downwind leg for a second approach. The value of ρ reacned 100 meters for about 3 seconds during the final turn in this approach (interval 6).

GENERAL OBSERVATIONS.

Meaningful test results were collected for five flights in 18 segments totaling 6.27 hours. Inspection of the JPO test configuration, analysis, and data plots led to several general cbservations:

1. A near real-time trajectory served as the reference flightpath. Such a choice represented a nonoptimized case for computing airborne receiver errors. On the other hand, it permitted a quick look of receiver performance at low cost.

2. The mean and rms errors were computed over the nominal 1,400-second segment against the nonoptimized reference trajectory. In addition, the Yuma program had some minor imperfections and removed error data beyond a given limit (typically for $\rho \geq 400$ meters).

3. The Z-set errors generally increased during turns. Vertical errors were generally larger than horizontal errors.

4. The local position errors, observed by the ground truth receiver, increased with increasing time from satellite upload. (NAVSTAR 1 and 2 were operating on quartz crystal clocks.) For most of the missions, the space segment errors were large (leading to local errors greater than 30 meters in the horizontal plane).

5. The mean horizontal errors (averaged over the nominal 1,400-second segments) between GPS airborne receivers closely agreed (typically to within 5 meters).

6. The mean horizontal errors between GPS airborne receivers closely correlated with errors recorded by the ground truth receiver (typically to within 6 meters). Thus, it is concluded that the major averaged error contribution in the horizontal plane to the Z-set came from the space segment (and not from the flight dynamics). The mean vertical errors for the Z-set did not track as well as the horizontal errors with other airborne receivers and with the fiducial receiver.

7. The Z-set generally did not "lose" a satellite during expedited maneuvers when the line-of-sight propagation link from the satellite to the GPS antenna was briefly lost, for example, during a 180° turn. However, the delta position parameters grew on successive occasions when the antenna was shielded from a setting satellite (NAVSTAR 4).

8. The Z-set is programmed to acquire or to drop satellites at elevation angles within 10° to 15° above the horizon. During two missions, the Z-set lost and did not recover NAVSTAR 4 when it was setting and estimated to be less than 20° above the horizon. Also, the Z-set lost one satellite during an emergency spiral descent and reacquired it during maneuver recovery. The navigation solution appeared to degrade/recover in a graceful fashion on all flights.

9. When navigating on three satellites plus barometric altitude input, the Z-set exhibited performance in the horizontal plane equivalent to four-satellite navigation.

10. The delta velocity curves for the Z-set usually reached over 10 meters per second (19.4 knots) during a turn or slightly dynamic maneuver. (The eight-state Kalman filter resident in the Z-set does not account for acceleration corrections and, hence, predicts straight line trajectories.) It was, therefore, decided to omit any analysis of the velocity behavior.

ANALYTICAL PROCEDURE.

The FAA analysis is based primarily on whether Z-set performance satisfies the horizontal navigation requirements for nonprecision approaches given by the Federal Radionavigation Plan (100 meters, 2 drms accuracy) (reference 2). The percentage of time, β, is computed when the instantaneous two-dimensional position difference, ρ, reaches or exceeds 100 meters during each flight segment. If $\beta<5$ percent during the nominal 1,400-second segment, then the receiver offers promise of meeting the requirements for nonprecision approaches. However, further analysis of position errors encountered during actual approaches must be made, and these will be addressed in the independent FAA test and evaluation program. As previously mentioned, approaches could not be adequately accomplished in the Yuma tests.

It was decided not to compute the error probability (assuming a multivariate normal distribution) from the mean and standard deviation values determined by the Yuma data reduction program. The reasons were the following:

1. Large space segment errors which contributed to most of the bias error in each direction (and which could, in principle, be subtracted from the mean).

2. Uncertainities in the accuracy of the reference path determination (from both the laser tracker and the employed filtering/smoothing algorithms) since the near real-time trajectory solution did not exclude all tracking system glitches resulting from losses in laser lock over very short periods, from lock changes between retroreflectors, and/or from intermittent changes between primary tracking lasers, especially during turns or sudden changes in aircraft attitude.

3. The availability of trajectory and error plots rather than the UFTIN and tracker data tapes.

4. The utilization of telemetered GPS data (from the C-141) in the computer-driven error plots rather than those recorded on the aircraft.

5. Removal of error data beyond extreme values (for example $\rho \geq 400$ meters).

6. Inconsistencies in the assignment of the filtered error limits, that is x, y, and z are bound by ±200 meters, but ρ and r are bound by 400 meters.

7. Inaccuracies/inconsistencies in the computation of the expected values, for example, the sum of the squares of the rms error components did not equal the square of the rms error vector (either two or three dimensions) due to reason number 6 (the same held for the mean and standard deviation), and, in some cases, when the error plots were noisy but within the assigned filtering bounds.

8. Unavailability of precise documentation on the Yuma tracking and data reduction analysis.

Although the Yuma determined expected error values were not utilized in the analysis, it is informative to summarize these results when large inconsistencies do not appear. For the missions described below, x, y, z, ρ, and r are tabulated in terms of the mean ($\bar{\alpha}$), rms (α_1), standard deviation (α_2), and extreme deviation(α_3). The quantity α_2 is computed from α_1 and $\bar{\alpha}$. The value of α_3 is read from the data plot. Pertinent position data are given to the nearest meter. The time of the segment is defined as the period over which the error data are available, even if some points are not included in the statistical computation. Onboard X-set or Y-set data, if available, are compared to Z-set results. In addition, the mean values are estimated for the filtered local errors determined by the ground truth receiver. A differential GPS analysis is not made by subtracting the averaged local errors. It is merely pointed out that the tabulated statistical parameters for the Z-set are heavily weighted by space segment errors.

SEPTEMBER 19 MISSION.

Data were taken over three consecutive flight segments totaling approximately 53 minutes; the expected values are given in table 1. An aided Y-set (aided by an inertial measurement unit) was also onboard to correlate results with the Z- . The local ground truth error in three dimensions exceeded 60 meters (limit on the data plot) by the end of the mission. The C-141 performed a spectrum of maneuvers including 180° turns at varied bank angles, an emergency spiral descent flight, approaches, and expedited climbs and descents. The parameter β = 6.6 percent in the first segment, which is illustrated in figure 2. Approximately 96 percent of the weight of β came from the spiral descent maneuver during which the Z-set lost and recovered a satellite. For the other flight segments, β = 1.4 and 1.8 percent. The horizontal mean errors for the Z-set tracked closely with those observed for the airborne Y-set and ground truth receiver.

NOVEMBER 27 MISSION.

This mission consisted primarily of racetrack patterns at 19,500 feet altitude. The aircraft did not perform any highly dynamic maneuvers except that the bank angle reached 45° in 180° turns. The local three-dimensional position error drifted upwards from approximately 40 to 110 meters. Data were taken for 61.5 minutes over three consecutive flight segments (see table 2). The parameter β = 0, 0, and 2.1 percent, respectively. In the final segment, ρ exceeded 100 meters (maximum excursion 143 meters) when the aircraft turned away (bank angles to 40°) from NAVSTAR 4 which was approaching the horizon. During this segment, the mean horizontal error for the Z-set closely tracked with the mean horizontal error (approximately [illegible]0 meters) recorded by the ground truth receiver.

NOVEMBER 30 MISSION.

Test data were collected over four segments lasting 91 minutes; the results are summarized in table 3. The C-141 performed a series of expedited/emergency maneuvers in the basic racetrack orbit, which included 180° turns and "S" turns, bank angles to 40°, continuous bank angle changes through 70°, roll rates to 10° per second, and pitch down/up from -12° to +18°. The mean local error in the horizontal plane varied between 39 and 52 meters, and the averaged three-dimensional error grew to 80 meters. The mean horizontal Z-set errors agreed closely with those recorded by the ground truth receiver. The parameter β = 3.3, 4.7, 3.4, and 12.6 percent for the respective segments. For almost the entire

TABLE 1. PARAMETERS FOR THE SEPTEMBER 19 MISSION

	Z-Set					Y-Set (Aided)					Ground Truth Receiver			
	x	y	z	ρ	r	x	y	z	ρ	r	x	y	z	r
Segment A, 1,260 seconds, β = 6.6%														
$\bar{\alpha}$				29		9	-10	8	14	17	10	-10	2	14
α_1				57		10	10	9	15	17				
α_2				49		4	3	4	5	4				
α_3				>400		19	16	21	20	23				
Segment B, 1,130 seconds, β = 1.4%														
$\bar{\alpha}$	20	-27	-7	36	44	19	-27	-13	33	36	14	-28	-13	34
α_1	27	30	23	40	51	19	27	15	33	37				
α_2	17	13	22	17	26	2	5	8	4	7				
α_3	150	-79	-160	152	217	24	-36	-28	40	46				
Segment C, 795 seconds, β = 1.8%														
$\bar{\alpha}$	12	-43		49							-2	-34		
α_1	24	45		51										
α_2	20	14		16										
α_3	133	-103		142										

Note: All α are in meters.

TABLE 2. PARAMETERS FOR THE NOVEMBER 27 MISSION

	Z-Set					Ground Truth Receiver			
	x	y	z	ρ	r	x	y	z	r
Segment A, 1,320 seconds, $\beta = 0$									
$\overline{\alpha}$	-5	36	45	41	66				
α_1	16	39	54	46	71				
α_2	15	14	29	21	26				
α_3	-62	73	161	88	177				
Segment B, 970 seconds, $\beta = 0$									
$\overline{\alpha}$	-1	43	74	45	87	0	44	55	70
α_1	13	45	78	46	89				
α_2	12	10	26	10	19				
α_3	58	81	158	92	167				
Segment C, 1,400 seconds, $\beta = 2.1\%$									
$\overline{\alpha}$	25	53	103	61	123	30	50	75	95
α_1	30	54	109	62	125				
α_2	16	11	34	13	24				
α_3	106	101	176	143	202				

Note: All α are in meters.

TABLE 3. PARAMETERS FOR THE NOVEMBER 30 MISSION

	Z-Set					Ground Truth Receiver			
	x	y	z	ρ	r	x	y	z	r
Segment A, 1,260 seconds, β = 3.3%									
$\bar{\alpha}$	35	-16	17	42	50	36	-16	4	40
α_1	38	22	28	48	55				
α_2	15	15	22	23	23				
α_3	<-200	>200	<-200	>400	>400				
Segment B, 1,400 seconds, β = 4.7%									
$\bar{\alpha}$	42	-30		53		44	-28	-20	56
α_1	46	32		55					
α_2	17	12		17					
α_3	130	-95		175					
Segment C, 1,400 seconds, β = 3.4%									
$\bar{\alpha}$	27	-36		50		30	-36	-40	62
α_1	34	39		53					
α_2	21	16		19					
α_3	-167	131		217					
Segment D, 1,400 seconds, β = 12.6%									
$\bar{\alpha}$	4	-53	64	64	92	4	-48	-64	8
α_1	27	57	69	69	96				
α_2	27	23	26	26	29				
α_3	197	<-200	136	378	379				

Note: All α are in meters.

final segment (β = 12.6 percent), the Z-set navigated on three satellites and the barometric altimeter input. NAVSTAR 4 was estimated to be less than 20° above the horizon when the Z-set lost it. It should be noted that NAVSTAR 4 made only a small contribution to the local position error as computed from four satellites.

DECEMBER 4 MISSION.

The Z-set was piggybacked on an aided X-set mission involving parachute drop tests. The C-141 crew flew slightly dynamic patterns over an 86-minute test period. The satellites exhibited relatively small user range errors. The mean horizontal errors recorded by the airborne and ground truth receivers closely correlated with each other (see table 4). The respective values for β over the four segments were 0, 0, 0, and 0.34 percent. The Z-set navigated on three satellites during the second half of the final segment when NAVSTAR 4 was less than 15° above the horizon. The filter limits for this mission were ±100 meters for single dimensional errors, and 200 meters for multidimensional errors.

DECEMBER 7 MISSION.

This mission consisted of constant altitude racetrack orbits with bank angles to 30° in 180° turns and roll rates 7° per second. Other than the expedited roll rates, the flight dynamics did not exceed those encountered in normal airline-type operations. The mean local errors in the horizontal plane were small for the period that data were available (see table 5). An unaided Y-set flew with the Z-set. The mean horizontal errors of the airborne receivers closely tracked with each other and with the available ground truth receiver errors. The Z-set lost NAVSTAR 4 in the final quarter of the third segment. NAVSTAR 4 was less than 20° above the horizon at this time. The Y-set continued to navigate on four satellites during the remainder of the test, while the Z-set utilized three satellites plus barometric altitude. The values of β for four segments covering 85 minutes were 0, 0, 3.0, and 1.7 percent, respectively.

SUMMARY AND CONCLUSIONS

Federal Aviation Administration (FAA) acceptance tests on the Navigation System Using Time and Ranging (NAVSTAR) Global Positioning System (GPS) Z-set were conducted by the Department of Defense (DOD) in an Air Force System Command (AFSC) C-141 aircraft over the Yuma instrumented range. Data from five flights totalling over 6 hours were divided in 18 segments, with a maximum duration of 1,400 seconds. The FAA analyzed the test results to determine whether the Z-set is capable of meeting civil requirements for nonprecision approaches: 100 meters, 2 distance root mean square (drms) accuracy or $\beta < 5$ percent, where β is the percentage of the time that the instantaneous horizontal error reaches or exceeds 100 meters. The receiver error is defined as the position difference between the receiver solution and the reference trajectory computed by the Yuma laser tracking system.

For three segments, $4.7 \leq \beta \leq 12.6$ percent. During these periods, the C-141 was performing expedited/emergency maneuvers and/or space segment errors were very large (yielding approximately 50 meter local errors in the horizontal plane). The upper limit occurred when both conditions applied and the Z-set was navigating on three satellites plus the barometric altimeter input. For the segment β = 6.6 percent, the aircraft made an emergency spiral descent at a 60° bank angle (2g

TABLE 4. PARAMETERS FOR THE DECEMBER 4 MISSION

	Z-Set					X-Set (Aided)					Ground Truth Receiver			
	x	y	z	ρ	r	x	y	z	ρ	r	x	y	z	r
Segment A, 1,155 seconds, β = 0														
$\overline{\alpha}$	7	-3	21	14	28						6	-6	8	12
α_1	12	15	28	20	34									
α_2	10	15	19	15	19									
α_3	43	25	75	48	82									
Segment B, 1,400 seconds, β = 0														
$\overline{\alpha}$	5	-9	14	14	25	8	-11	-3	13	14	8	-9	-2	12
α_1	11	11	21	16	26	8	11	7	14	15				
α_2	10	8	16	7	8	2	2	7	2	2				
α_3	36	-31	57	44	61	-29	-17	-14	33	34				
Segment C, 1,400 seconds, β = 0														
$\overline{\alpha}$	-2	-16	10	19	25	0	-16	-16	16	23	2	-14	-16	21
α_1	10	18	16	20	27	4	16	17	17	24				
α_2	10	8	13	8	11	4	2	5	2	4				
α_3	-62	-37	<-100	63	135	-8	-21	-30	22	33				
Segment D, 1,190 seconds, β = 0.34%														
$\overline{\alpha}$	-14	-17		27										
α_1	18	21		30										
α_2	12	12		14										
α_3	-98	-46		107										

Note: All α are in meters.

TABLE 5. PARAMETERS FOR THE DECEMBER 7 MISSION

	Z-Set					Y-Set (Unaided)					Ground Truth Receiver			
	x	y	z	ρ	r	x	y	z	ρ	r	x	y	z	r
Segment A, 1,395 seconds, $\beta = 0$														
$\bar{\alpha}$	0	16	42	20	48	1	14	33	17	38	2	14	26	30
α_1	12	19	47	22	52	10	16	33	19	38				
α_2	12	10	20	10	18	10	7	6	7	6				
α_3	-60	55	138	79	145	56	52	62	71	83				
Segment B, 1,400 seconds, $\beta = 0$														
$\bar{\alpha}$	8	13	47	20	53	8	14	33	19	40	10	12	23	28
α_1	14	17	52	22	57	18	18	34	26	43				
α_2	12	12	22	11	21	16	12	7	17	16				
α_3	91	58	-145	96	180	>200	182	79	281	284				
Segment C, 1,395 seconds, $\beta = 3.0\%$														
$\bar{\alpha}$	13	9		25		15	8		22					
α_1	23	21		34		22	19		33					
α_2	19	20		24		17	17		24					
α_3	>200	-190		338		>200	>200		>400					
Segment D, 900 seconds, $\beta = 1.7\%$														
$\bar{\alpha}$	9	-3	46	29	55	10	1	14	15	23				
α_1	25	21	47	32	57	19	12	16	22	27				
α_2	23	21	6	15	14	16	12	8	16	15				
α_3	177	108	116	207	238	100	97	50	124	127				

Note: All α are in meters.